12

Radiological Dose Assessment

Robert J. Harrach
Gretchen M. Gallegos

Introduction

Radiological doses to the public result from both natural and man-made radiation. The total dose to different populations can be determined by measurements and calculations. This chapter describes LLNL's radiological dose assessments, made to determine the impact of LLNL operations, and contains a discussion of the analyses we performed to demonstrate LLNL's compliance with the radiological National Emission Standards for Hazardous Air Pollutants (NESHAPs; 40 CFR 61 Subpart H).

Because this report has a diverse readership, we have included a brief tutorial on radiation—describing the different sources and types of radiation and the units used to quantify it, and providing some perspective on the wide range of radiation levels people commonly encounter—to enable the nonspecialist to understand more easily the radiological dose assessment information we report; see Supplement 12-1: "Radiation Basics," at the end of this chapter. The organization of the main text is to briefly summarize the federal standards for radiation protection, describe the basic models, data files, and concepts we use, comment on our facilities and the way potential and actual releases of radionuclides are determined, and present and put in context the main results from our radiological dose assessment for 1996 activities. Two additional supplements provide ancillary information; Supplement 12-2 describes LLNL's standard operating procedures that protect employees and the public from uncontrolled releases and unsafe levels of radiation, and Supplement 12-3 discusses modeling doses from explosives experiments at LLNL's Experimental Test Site, Site 300.

Radiation Protection Standards

DOE environmental radiation protection standards are provided in DOE Order 5400.5, *Radiation Protection of the Public and the Environment* and federal regulation 10 CFR 835, *Occupational Radiation Protection,* which incorporate standards for controlling exposures to the public from operations at DOE facilities. These standards are based on recommendations by the International Commission on Radiological Protection

(ICRP 1977, 1980) and the National Council on Radiation Protection and Measurements (NCRP 1987a). The primary DOE radiation standards for protection of the public are 1 mSv/y (100 mrem/y) effective dose equivalent (EDE) for prolonged exposure, and 5 mSv/y (500 mrem/y) EDE for occasional exposure. (Radiation units and other terms are described in Supplement 12-1.) These limits are based on the dose to the maximally exposed individual in an uncontrolled area, and include all pathways of exposure. The limits apply to the sum of the EDE from external radiation and the committed (50-y) EDE from radioactive materials that may remain in the body for many years after being ingested or inhaled.

DOE and LLNL also comply with the EPA's standard for radiation protection, promulgated under Section 112 of the Clean Air Act, as amended. This EPA radiation dose standard, which applies only to air emissions, is defined in Subpart H of NESHAPs under 40 CFR 61. It limits to 0.1 mSv/y (10 mrem/y) the whole-body EDE to members of the public from air emissions at DOE facilities under 40 CFR Part 61.92, Subpart H. Additionally, NESHAPs requires under Part 61.93 that any individual operation or activity that has the potential to produce an annual-averaged dose to a member of the public greater than or equal to 0.001 mSv/y (0.1 mrem/y) (i.e., greater than or equal to one percent of the threshold level cited above for site-integrated emissions), allowing no credit for emission control devices, must be continuously monitored using EPA-approved methods.

Because the EPA standard is a low dose level, compared to doses from exposures to natural radioactivity (see Supplement 12-1) and doses caused by radionuclides released from DOE facilities are generally smaller still, it would be difficult to prove compliance with the standard by environmental measurements alone. EPA therefore developed computer codes that implement its approved dosimetry model and mandated that these codes be used to calculate potential doses to the public for compliance demonstrations. The models used in the regulatory codes to evaluate doses and risks contain conservative assumptions that are expected to result in calculated doses larger than ones actually received by members of the public. Calculations reported here primarily were performed using EPA's CAP88-PC code, described below.

Modeling Code and LLNL Data Files

The CAP88-PC code, developed under an Interagency Agreement between DOE and EPA and made available early in 1992, provides the capability to compute dose and risk to both exposed individuals and collective populations resulting from radionuclide emissions to air. The differences between CAP88-PC and earlier similar codes such as

AIRDOS-PC are discussed in Appendix E of the *User's Guide for CAP88-PC, Version 1.0* (Parks 1992). The mathematical models and explicit equations used in CAP88-PC are described in Chapter 8 of the *User's Guide*.

CAP88-PC uses a modified Gaussian plume equation to calculate the average dispersion of radionuclides released from up to six collocated sources. Plume rise can be driven by momentum, buoyancy, or set to a predetermined level. Flat terrain is assumed. CAP88-PC accommodates stack sources and area sources. For each stack, the key parameters to be specified are total emissions during the year (e.g., total number of becquerels [Bq] or curies [Ci] for each radionuclide), and stack flow rate, height, diameter, abatement devices, and location relative to site boundaries. Similar input data is required for area sources.

These source options are well-suited to LLNL's Livermore site, which has more than 200 stacks divided among several dozen buildings containing facilities where radioactive materials are used, stored, or where activation products occur, called Radioactive Materials Management Areas (RMMAs). Additionally, a dozen diffuse area sources have been identified at the Livermore site and Site 300. The way these various sources are characterized for input to computer modeling runs is discussed below under the headings "Inventoried Sources" and "Monitored Sources." But the principal sources of radionuclide air emissions at Site 300 are not conventional; these are several "firing tables" where open-air explosive experiments are conducted, and their specification is more complicated (see Supplement 12-3 at the end of this chapter).

Up to 36 radionuclides can be included in a single run, chosen from a library of 265 radionuclides. Because CAP88-PC does not contain all the radionuclides present at LLNL, surrogate radionuclides were used in some cases to estimate EDEs. In selecting the surrogates, we used the most restrictive lung class (whether clearance from the lungs takes place in days, weeks, or years). When possible, we used a surrogate radionuclide with similar lung class chemistry and similar values for "annual limits of intake via inhalation and derived air concentration," as specified in the EPA guidance, *Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion* (Eckerman et al. 1988).

CAP88-PC employs a circular grid, allowing up to 20 user-selected radial distances. Concentrations and doses are sector-averaged for each selected radius. For specifying populations, each area element in the sixteen 22.5° compass sectors is bounded above and below by arcs with radii from the set of user-selected distances and on its sides by radial line segments separating the sectors. The code contains several modeling options regarding agricultural characteristics and land use, as established by the EPA.

The population in each of these area elements can be set by a user-created population data input file. This file specifies the population distribution out to a radius of 80 km from a facility, considered by EPA to be the range of the exposed population. In 1996, we constructed improved versions of the population distributions centered on the two LLNL sites. These distributions are based on 1990 census data, as were the previous ones, but were made more accurate through use of commercially available, computer-map-based population data and ArcView© geographic information system software. The population for each sector area segment was determined by selecting census block level data for that segment. Key population centers affected by LLNL emissions are the relatively nearby communities of Livermore and Tracy, and the more distant metropolitan areas of Oakland, San Francisco, and San Jose, as well as the San Joaquin Valley communities of Modesto and Stockton. Within the 80-km outer distance specified by the EPA, there are 6.3 million residents included for the Livermore site collective dose determination, and 5.2 million for Site 300. Our new population data files (distribution of population with distance and direction) are published in the *LLNL NESHAPs 1996 Annual Report* (Gallegos and Biermann 1997).

CAP88-PC accepts site-specific meteorological, as well as population, data files. Input data for the LLNL modeling are collected from on-site meteorological towers at both the Livermore site and Site 300. Wind speed and direction are sampled every few seconds, temperature every minute, and all are averaged into quarter-hour increments, time-tagged, and computer-recorded for conversion into a CAP88-PC wind file. Data specifying the annual average precipitation, temperature, and average height of the atmospheric inversion layer are also put into the model. CAP88-PC computes results for each of seven Pasquill-Gifford atmospheric stability categories, specified as part of the wind file. Chapter 1, Site Overview, in this report discusses the LLNL meteorological data, and exhibits wind roses for both LLNL sites.

CAP88-PC computes radionuclide concentrations in air, rates of deposition on ground surfaces, concentrations in food, and intake rates to people from ingestion of food produced in the assessment area. The code contains the EPA's approved dosimetry model, allowing calculation of doses from each of the four principal exposure pathways: internal exposures from inhalation of air and ingestion of foodstuffs and drinking water, and external exposures through irradiation from contaminated ground and immersion in contaminated air. Dose and risk are tabulated as a function of radionuclide, pathway, spatial location, and body organ.

Dose and risk estimates from CAP88-PC are applicable only to low-level chronic exposures because the health effects and dosimetric data it uses are based on low-level chronic intakes. The code is not intended for modeling either short-term or high-level

radionuclide intakes. The doses are expressed as whole-body effective dose equivalents (EDEs) in units of mrem / y (1 mrem = 10 μSv = 0.01 mSv).

Maximally Exposed Individuals and Populations

We report separate determinations of doses resulting from releases of radioactivity to air from the Livermore site and Site 300. Three potential doses are emphasized: (1) the dose to the sitewide maximally exposed individual member of the public (denoted as SW-MEI and defined below), which integrates the effects of all emission points at a site; (2) the maximum dose to any member of the public, in any direction (generally occurring at the site boundary and commonly referred to as the maximum "fence line" dose), caused by each individual source of emissions on the site; and (3) the collective dose to the populations residing within 80 km of the Livermore site and Site 300 (treated separately), adding the products of individual doses received and the number of people receiving them. Dose to the SW-MEI (the first type above) is used to evaluate LLNL's compliance with the EPA standard limiting the total radionuclide emissions to air from DOE facilities to 100 μSv / y (10 mrem / y). In this evaluation, credit is taken in the dose model for any emission abatement devices, such as filters. The second type, or fence line dose, is calculated without taking credit for emission abatement devices; it is used to evaluate the need for continuous monitoring of individual emission points under the EPA's 1-μSv / y (0.1-mrem / y) standard on potential unabated emissions.

The SW-MEI is defined as the hypothetical member of the public (individual receptor at a residence, place of business, school, church, or similar public facility) who could receive the greatest LLNL-induced EDE from the combined effect of all sources at a single site. At the Livermore site, the SW-MEI is located at the UNCLE Credit Union, about 10 m outside the controlled eastern perimeter of the site. This location lies 0.95 km from LLNL's principal source of radionuclide emissions to air, the Tritium Facility (Building 331), in an east-northeast direction. At Site 300, the SW-MEI is located in an experimental area termed "Bunker 2" operated by PRIMEX / Physics International. Bunker 2 lies about 300 m outside the east-central boundary of Site 300. This bunker is 2.4 km east-southeast of the principal source of radionuclide emissions to air at Site 300, the firing table at Building 801.

It is possible for the location of the SW-MEI to change from year to year, e.g., with changing wind patterns, changing population distributions near site boundaries, or changing emission levels of sources. An illustration of the effect of different wind patterns on dose is given in the *LLNL NESHAPs 1993 Annual Report* (Harrach et al. 1994).

Four prime candidates for the SW-MEI were evaluated for the Livermore site in confirming the UNCLE Credit Union location for 1995, as described in the *LLNL NESHAPs 1995 Annual Report* (Gallegos et al. 1996).

As stated above, this dose evaluation only pertains to air releases. Releases of radioactivity to the environment during LLNL operations occur via the water pathway as well as air. But radionuclides deposited into surface and ground waters by LLNL operations are not consumed by any individual, and of course releases to the sanitary sewer are not consumed. Therefore these releases to sewer, surface, and ground waters (which are discussed in Chapters 6, 7, and 8 of this report) do not represent a direct ingestion or inhalation pathway for radiation exposure of the public, and are excluded from our radiological dose assessment. Any possible indirect exposures to the public from releases to LLNL waters, e.g., inhalation dose from exposure to sludge containing sewered material, would be treated as special cases and clearly identified as such in reporting dose. Finally, no public exposures occurred via the direct radiation pathway from LLNL operations in 1996.

Monitored and Inventoried Sources

Accurate characterization of emission sources is crucial to credible air dispersion and dose modeling, and more generally to gauging the impacts of LLNL operations on workers, the public, and the environment. LLNL's sources are determined in three principal ways—by an inventory process, by direct measurement (monitoring) of the emission at the source, and by monitoring selected field points in and around the site.

Inventoried Sources

Earlier we defined Radioactive Materials Management Areas (RMMAs) as areas where radioactive materials are used or stored, or where activation products occur. Several RMMAs at the Livermore site have effluent monitoring systems in place in their exhaust pathways, as discussed below, allowing a direct measurement of their emission rates. For unmonitored or noncontinuously monitored RMMAs, source terms for potential releases are inferred from radionuclide inventories.

Inventory data is provided by experimenters and facility managers. A full inventory is not conducted each year; only the "key" Livermore site facilities, defined as those that accounted for 90% of the previous year's (1995) Livermore site radiological dose to members of the public, were reinventoried for 1996. (LLNL conducted a complete radionuclide-inventory update in 1994.) In addition, all new RMMAs (ones that

commenced operations in 1996) were inventoried. Radionuclide inventories for all Site 300 explosives experiments were also updated in 1996.

For purposes of dose modeling, radionuclide inventory data is converted to potential release rates by means of EPA-specified multipliers for materials in different physical states—solid, liquid, powder, or gas—in accordance with 40 CFR Part 61, Subpart H, Appendix D. If the material was an unconfined gas, the release fraction 1.0 was used; for liquids and powders, 1.0×10^{-3} was used; and for solids, 1.0×10^{-6} was used.

In addition, for inventoried facilities credit was taken for radionuclide emission control devices when calculating total dose for evaluation under the 10 mrem/y (100 μSv/y) EPA standard. Similar to physical-state factors, EPA also specifies control-device abatement factors, associated with various emission-control devices, for use in dispersion and dose models: each high-efficiency-particulate-air (HEPA) filter stage is given a 0.01 emission-reduction factor, venturi scrubbers and electrostatic precipitators are each given a 0.05 factor, and each activated-charcoal filter is given a 0.1 factor. Emissions were assumed to be unabated for evaluations under the 1 μSv/y (0.1 mrem/y) EPA standard for required continuous monitoring.

In summary, for unmonitored and noncontinuously monitored sources, estimated annual emissions for each radionuclide are based on the product of (1) radionuclide quantity from inventory data, (2) EPA potential-release fractions (physical-state factors), and (3) applicable emission-control-device abatement factors.

Monitored Sources

Effluent Monitoring

Actual measurements of radionuclides in air and effluent flow are the basis for reported emissions from continuously monitored sources (replacing the product of inventory data and release-to-air and emission-abatement factors above). There are currently nine buildings at the Livermore site that have continuously monitored discharge points: Buildings 166, 175, 231 (vault area), 251, 331, 332, 419, 490, and 491. These monitoring systems are described in the *LLNL NESHAPs 1996 Annual Report* (Gallegos and Biermann 1997). Taken together, these buildings feature 103 continuously-operating monitors. (See Chapter 5.)

The most significant monitored source is the Tritium Facility, Building 331, at the Livermore site. Each stack of this facility features both a continuous-monitoring alarm system and continuous molecular-sieve samplers. The sieve samplers, which can discriminate between tritiated-water vapor (HTO) and molecular tritium (HT), provide the values used for environmental reporting. The alarmed samplers provide real-time

tritium concentration release levels (HT and HTO). Monitoring of these stacks provides an accurate measure of the total quantity (number of becquerels or curies) of tritium released to the environment, time-resolved over the course of the year, from stacks of known properties (height, flow rate, and diameter) into a wind field of continuously monitored properties (wind speed, direction, and fluctuation characteristics). This directly measured data on emission rates and wind field distributions significantly improves the quality and credibility of the air dispersion and dose assessment modeling.

Effluent monitoring in the other eight facilities is designed to detect radioactive particles. In contrast to monitoring unabated flow of tritium gas in the Building 331 stacks, air samples for particulate emissions are extracted downstream of HEPA filters and prior to the discharge point to the atmosphere. Particles are collected on membrane filters. Sample results are generally found to be below the minimum detectable concentration (MDC) of the analysis; sometimes as few as 1 to 4 samples (out of 25 to 50 per year) have concentrations greater than the MDC. Reporting zero values for this type of data can be justified; for details, see Chapter 5, Air Effluent Monitoring, in this report, and the previously cited 1996 NESHAPs Report.

Among the nine continuously monitored facilities at the Livermore site, none strictly requires monitoring under the EPA's 1 μSv / y (0.1 mrem / y) standard; each is continuously monitored for programmatic and other reasons. For example, continuous monitoring is maintained at the Tritium Facility to provide the most direct and accurate measure of its release of tritium to the atmosphere, and continuous monitoring is maintained at the Plutonium Facility (Building 332) and the seismically-hardened portion of Building 251 in lieu of undertaking a modeling and measurement effort that would be required to demonstrate that monitoring is not needed.

Dose calculations based on effluent monitoring data are expected to be more accurate than those using assumptions based on inventory data, physical state release fractions, and emission-control factors.

Surveillance Monitoring

Beyond the stack effluent monitoring, site-specific surveillance air monitors are placed in the vicinity of diffuse emission sources on site, in particular, those associated with Buildings 292, 331, 514, and 612 and in and around the southeast quadrant of the Livermore site. These special monitors measure the concentrations of radionuclides present in the air near the sources and allow a direct determination of their environmental impact.

Estimate of Total Radioactivity Released

Source information obtained from effluent and surveillance monitoring and the inventory process provides an estimate of the total amount of radioactivity released from LLNL, with a breakdown by individual isotopes. As discussed in Chapter 5 of this report (see especially **Table 5-3** and **Figure 5-2**), the total for 1996 was slightly higher than in 1995, but was below the range of earlier years.

Calculations of Radiological Dose

More than 200 point sources were included in the 1996 modeling runs, representing stack emissions from all RMMAs in which radiological operations took place.

In addition to these point sources, there are several diffuse sources at both sites. Building 514 and five other Livermore-site sources external to buildings, including the RMMA at the Building 612 Hazardous Waste Management Yard, were treated as diffuse-area sources, as were six Site 300 sources, including the ground area around the firing tables where surface and subsurface contamination exists. Finally, explosives experiments were conducted at two Site 300 explosives-testing facilities—the firing tables associated with Buildings 801 and 851—during 1996, and were modeled in our customary way (see Supplement 12-3), using inventory data and scaling laws for open-air explosives experiments. This section presents the main results of our calculations. For further details, especially regarding the diffuse sources at the two sites, see the *LLNL NESHAPs 1996 Annual Report* (Gallegos and Biermann 1997).

Dose Breakdown by Facility

Table 12-1 lists all LLNL facilities and diffuse sources having the potential to release radioactivity into the environment during 1996. For each facility or building, the table gives the number of stacks discharging radionuclides, lists the dose to a public individual caused by the dominant emission point at each facility, and identifies the types of operations occurring in the building or facility, or the nature of the diffuse source, as the case may be. Corresponding data is included for the Site 300 explosive experiments. Facilities in which no operations using radionuclides took place in 1996 or in which any radionuclides present were encapsulated or sealed for the entire year are excluded from **Table 12-1**.

The principal feature shown in the table is that LLNL has a fairly large number of very small sources. As shown more clearly in subsequent tables, a few sources account for nearly all of the dose to members of the public, and the total dose is quite small compared to federal standards for radiation protection of the public.

Table 12-1. Sources of radiation dose from LLNL releases to air: stacks (on buildings containing radioactive materials management areas) and diffuse area sources.[a,b]

Bldg	Facility	Potential emission points	Maximum EDE[c] (μSv/y)	Operations
131	Engineering	3	1.8×10^{-4}	Large office/laboratory facility housing Mechanical and Electrical Engineering Divisions; materials processing and storage
151	Isotope Sciences; Chemistry & Materials Science Environmental Services Lab	23	1.9×10^{-4}	Application of nuclear and isotope sciences to a wide range of problems; sample analysis of waste streams and environmental media for radionuclide content
166	Laser Isotope Separation	1	0.0[d]	Conversion of uranium to halides and oxides
175	Laser Isotope Separation	1	2.3×10^{-3}	Cleaning and refurbishing of uranium parts
177	Laser Isotope Separation	5	2.8×10^{-2}	Sample preparation, cleaning of parts, processing uranium oxide powders, liquid uranium corrosion studies
194	Physics & Space Technology	2	2.5×10^{-4}	High-energy linear accelerator (LINAC), positron beam generation and experiments
212	Physics & Space Technology	2	8.0×10^{-11}	Physics experiments; residual contamination from previous operation of rotating target neutron source (no longer operating)
222	Chemistry & Materials Science	18	1.1×10^{-6}	Chemical analyses, cleaning equipment, waste samples preparation and analysis, decontamination, spectroscopy, gravimetric
224	Chemistry & Materials Science	4	1.0×10^{-4}	Chemical analysis, waste collection, sample digestion
226	Chemistry & Materials Science	2	1.2×10^{-9}	Sample preparation, scintillation counting
231	Chemistry & Materials Science, Engineering, Safeguards & Security	13	2.8×10^{-6}	Materials research and testing, spin forming, heat treatment, electron-beam welding, grinding/polishing, casting, microscopy, sample preparation, storage
	Mechanical Engineering Vault	1	0.0[d]	Storage of radionuclides
235	Chemistry & Materials Science	5	2.7×10^{-7}	Material structure studies, precision cutting, ion implantation, metallurgical studies
241	Chemistry & Materials Science	4	3.7×10^{-10}	Materials properties research and testing
251	Heavy Elements			Storage of transuranic isotopes prior to disposal
	Seismically Hardened area	4	0.0[d]	
	Unhardened areas	33	7.7×10^{-4}	
253	Hazards Control	12	7.3×10^{-9}	Radiochemical analyses
254	Hazards Control	5	5.6×10^{-11}	Radiochemical analyses of bioassays; analytical services
255	Hazards Control	2	1.0×10^{-4}	Radiation standards and instrument calibration
281	Chemistry & Materials Science	8	2.1×10^{-8}	Sample preparation; wet chemistry laboratory
282	Physics & Space Technology	1	0.0	Non-operational facility with tritium contamination
292	Environmental Programs	3	7.3×10^{-5}	Tritium contamination from prior operations

Table 12-1. Sources of radiation dose from LLNL releases to air: stacks (on buildings containing radioactive materials management areas) and diffuse area sources[a,b] (continued).

Bldg	Facility	Potential emission points	Maximum EDE[c] (μSv/y)	Operations
298	Laser Fusion	2	1.1×10^{-4}	Laser fusion targets research and development
321	Materials Fabrication	4	4.2×10^{-6}	Forming, machining, and manufacturing of uranium parts
322	Mechanical Engineering	1	8.0×10^{-8}	Cleaning and plating of depleted uranium
327	Mechanical Engineering	1	1.3×10^{-8}	Nondestructive ultrasonic material evaluation
331	Tritium	2	4.2×10^{-1}[d]	tritium research; decontamination and decommissioning operations
332	Plutonium	7	0.0[d]	Plutonium research
361	Biological and Biotechnology Research	15	1.1×10^{-5}	Radiolabeling; biological dosimetry; DNA sequencing, hybridization, and repair; human genome; enzyme assay; radioactive probes
362	Biological and Biotechnology Research	1	2.2×10^{-7}	Dose preparation for animal experiments
363	Biological and Biotechnology Research	1	1.9×10^{-5}	Dispensing samples
364	Biological and Biotechnology Research	2	6.3×10^{-5}	DNA labeling; isolation and purification
365	Biological and Biotechnology Research	1	6.4×10^{-12}	Housing research animals
378	Health and Ecological Assessment	2	1.5×10^{-9}	Chemical and radiological sample preparation for environmental analyses; analysis of environmental samples
381	Laser Fusion	1	2.7×10^{-13}	Tritium handling for laser target research
391	NOVA Laser	1	3.5×10^{-4}	Housing of high-energy laser; fusion target irradiation
412W	Health and Ecological Assessment	1	2.3×10^{-12}	Sample preparation for measurement of Ni-59 and Ni-63
419	Hazardous Waste Management	2	1.0×10^{-3}[d]	Decontamination and decommissioning
490	Laser Isotope Separation	1	0.0[d]	U.S. Enrichment Corporation isotope separation operations, including vaporization of uranium for enrichment
491	Laser Isotope Separation	1	0.0[d]	U.S. Enrichment Corporation isotope separation operations
513	Hazardous Waste Management	1	3.8×10^{-7}	Drum repacking and sludge stabilization
514	See diffuse sources below			
612	Hazardous Waste Management	1	6.3×10^{-5}	Waste repackaging for shipment offsite

Table 12-1. Sources of radiation dose from LLNL releases to air: stacks (on buildings containing radioactive materials management areas) and diffuse area sources[a,b] (concluded).

Bldg	Facility	Potential emission points	Maximum EDE[c] (μSv/y)	Operations
801	Site 300 Firing Table at 801	—[e]	1.8×10^{-1}	Detonation of explosives
851	Site 300 Firing Table at 851	—[e]	1.5×10^{-1}	Detonation of explosives
	Livermore site diffuse sources[f]	6	See next six entries below	Storage areas and contaminated ground
292	Underground storage tank	1	3.6×10^{-6}	Tank leakage of tritiated water; transpired by plants
331	Tritium Facility (external)	1	3.1×10^{-2}	Outdoor waste accumulation area
514	Hazardous Waste Management Tank Farm	1	3.0×10^{-1}	Liquid waste processing, treatment, and storage
612	Hazardous Waste Management	1	2.5×10^{-1}	Storage of low-level waste
—	Southeast quadrant of Livermore site	1	9.4×10^{-3}	Contaminated ground
	Site 300 diffuse sources[f]	6	See next six entries below	Contaminated ground and water
—	Pit 7 Complex	1	3.0×10^{-4}	Contaminated ground and purge water
802	Site 300	1	5.4×10^{-7}	Contaminated ground
850	Site 300	1	5.7×10^{-5}	Contaminated ground
851	Site 300	1	1.8×10^{-7}	Contaminated ground
—	Well 8 Spring	1	1.3×10^{-6}	Contaminated spring water
—	All Site 300 land area	1	4.1×10^{-3}	Contaminated ground

a *LLNL NESHAPs 1996 Annual Report* (Gallegos and Biermann 1997).

b RMMAs in which no operations using radionuclides took place in 1996 or in which all radionuclides were encapsulated or sealed for the entire year are not included in this table. Table entries refer to routine operations, not unplanned releases.

c The maximum effective dose equivalent to the sitewide maximally exposed individual (SW-MEI) member of the public from a single discharge point, among all discharge points modeled for the indicated facility or building. The SW-MEI is defined in the section on Maximally Exposed Individuals and Populations.

d The effluents from the facility are monitored. Zeroes refer to monitored values below the minimum detectable concentration, as discussed in the Monitored Facilities section.

e Open air dispersal in 1996.

f Diffuse sources are described briefly in the section on specifications of source terms, and more fully in the *LLNL 1996 NESHAPs Annual Report* cited in footnote a.

Unplanned Releases

The foregoing discussion, as well as all entries in **Table 12-1**, refer to releases occurring during the course of normal operations. Unplanned or accidental releases must be accounted for, as well, in determining the total dose to the public from LLNL activities. As noted in Chapter 2 of this report (in the subsection on "National Emission Standards for Hazardous Air Pollutants"), there was one unplanned atmospheric radionuclide release from the Livermore site in 1996, involving leakage of 1.5 L of oil contaminated with depleted uranium from a 55-gal drum in the Building 514 yard. The calculated dose to the SW-MEI from this event was extremely small: 4.9×10^{-8} μSv (4.9×10^{-9} mrem). There were no unplanned atmospheric releases at Site 300 in 1996.

Doses to Sitewide Maximally Exposed Individuals

The 1996 calculated EDE to the SW-MEI from Livermore-site point sources was 0.48 μSv (0.048 mrem). Emissions from the two 30-meter stacks at the LLNL Tritium Facility (Building 331) accounted for 0.45 μSv (0.045 mrem). In 1995, emissions from the Tritium Facility resulted in a modeled dose of 0.17 μSv (0.017 mrem). The relative increase in 1996 in emissions and dose occurred primarily as a result of glovebox decontamination and decommissioning activities. For the Livermore site, the dose calculated for the SW-MEI from diffuse emissions in 1996 was 0.45 μSv (0.045 mrem). When point and diffuse sources were combined, the total annual dose was 0.93 μSv (0.093 mrem), divided 52%/48% between point and diffuse source emissions.

The calculated EDE to the SW-MEI at Site 300 was 0.33 μSv (0.033) mrem from point-source emissions. All of this EDE resulted from Building 801 and Building 851 firing-table emissions in the course of explosives experiments—55% from the former and 45% from the latter. This is an increase over the 0.20 μSv (0.020 mrem) dose modeled for 1995; the larger dose resulted from an increase in the amount of depleted uranium used in experiments at the site. **Table 12-2** shows the dose values attributed to firing table experiments for 1990 through 1996, correlated with the total amounts of depleted uranium and the total quantity of high explosives used in the experiments. (Only experiments that included depleted uranium are considered; most have none.) The data show that variations from year to year in these doses mainly reflect differences in the amount of depleted uranium used in the tests. For Site 300, only 0.0045 μSv (0.00045 mrem), or 1%, was contributed by diffuse sources. Resuspension of LLNL-contributed uranium in surface soils throughout Site 300 was responsible for nearly all of this dose from diffuse sources.

Table 12-2. Annual dose to the SW-MEI from explosives experiments on firing tables at Site 300, 1990–1996, related to the total quantity of depleted uranium used in the experiments and the total quantity of high explosives (HE) driving the detonations.

Year	Dose to SW-MEI		Total depleted U used in experiments (kg)	Total HE used in depleted U experiments (kg)
	(μSv)	(mrem)		
1996	0.33	0.033	272	112
1995	0.20	0.020	165	199
1994	0.49	0.049	230	134
1993	0.11	0.011	99	74
1992	0.21	0.021	151	360
1991	0.44	0.044	221	330
1990	0.57	0.057	340	170

Table 12-3 lists the facilities that were primarily responsible for the LLNL dose; the contributions from all emission points at each facility have been summed. These facilities accounted for approximately 99.8% of the total EDE resulting from Livermore site operations and practically 100% of the total EDE from Site 300 operations. The dominant radionuclide(s) are indicated for each facility. Tritium was the overall dominant radionuclide at the Livermore site, accounting for more than two-thirds of the Livermore site dose. At Site 300, practically the entire dose was due to the isotopes present in depleted uranium having atomic numbers 238, 235, and 234.

The relative significance of inhalation and ingestion is different for tritium and uranium and depends on the assumptions made about the origin of food consumed by a person receiving the dose. For the conditions we assumed when assessing individual doses, namely that milk is imported while the remainder of the food is produced locally, ingestion accounted for 81% of the dose in the case of tritium, versus 19% for inhalation. For uranium, these numbers are nearly reversed: 17% by the ingestion pathway, versus 83% via inhalation. For both uranium and tritium, external doses from air immersion and ground irradiation were negligible.

The trends in dose to the SW-MEI from emissions at the Livermore site and Site 300 over the last 7 years are shown in **Figure 12-1** and **Table 12-4**. No diffuse emissions were reported at Site 300 for years before 1993, so comparison for total dose can only be made with the values for 1993, 1994, and 1995; in addition, diffuse source doses were not reported separately from the total dose for the Livermore site for 1990 and 1991. As noted earlier, the increased point source contribution to dose for the Livermore site for 1996 compared to 1995 is attributed to glovebox decontamination and decommissioning operations at Building 331. The increased diffuse source contribution to dose is attributed to increased treatment of legacy waste at the Building 514 Tank Farm.

Table 12-3. Major contributors to LLNL's radiation dose via airborne emissions, 1996.

Facility or operation[a]	Dominant radionuclide(s)	EDE at SW-MEI[b]	
		μSv/y	mrem/y
Livermore site			
B331/Tritium Facility	^{3}H	0.45	0.045
B612 Yard Area[c]	^{3}H	0.25	0.025
B514/Tank Farm[c]	^{238}U, ^{228}Th, ^{239}Pu, ^{137}Cs, ^{234}U	0.16	0.016
B331/Exterior[c]	^{3}H	0.031	0.0031
B177/U-AVLIS	^{238}U, ^{234}U, ^{235}U	0.028	0.0028
S.E. Quadrant	^{239}Pu	0.0092	0.00092
Sum of all other sources	Various	0.0018	0.00018
Total		**0.93[d]**	**0.093[d]**
Site 300			
B801/firing table	^{238}U, ^{234}U, ^{235}U	0.18	0.018
B851/firing table	^{238}U, ^{234}U, ^{235}U	0.15	0.015
Soil resuspension[c]	^{238}U, ^{234}U, ^{235}U	0.0041	0.00041
Total		**0.33[d]**	**0.033[d]**

a The facilities cited here are discussed in the text of this report and in more detail in the NESHAPs annual reports.

b These doses represent the sum of all emission points from a given facility (for example, both stacks on Building 331), in contrast to the dose values in **Table 12-1**, which represent the dose from the single largest emission point on each facility. The sitewide maximally exposed individual (SW-MEI) member of the public is defined in the section on Maximally Exposed Individuals and Populations.

c Diffuse sources (see text).

d These Livermore site and Site 300 totals represent 0.9% and 0.3%, respectively, of the federal standard.

Collective Doses to Exposed Populations

Population doses, or collective EDEs, for both LLNL sites were calculated out to a distance of 80 km in all directions from the site-centers using CAP88-PC. As noted earlier, CAP88-PC evaluates the four principal exposure pathways: ingestion through food and water consumption, inhalation, air immersion, and irradiation by contaminated ground surface. The collective EDE due to 1996 Livermore-site operations was 1.1 person-rem (0.011 person-Sv), of which 0.88 person-rem (0.0088 person-Sv), or 80%, was from point-source emissions, and the remaining 20% from diffuse sources. This value is greater than the 1995 result of 0.59 person-rem (0.0059 person-Sv). The reason is the increased stack releases in 1996. Stacks release effluents at considerable speed high above the ground, allowing contaminants to be more readily transported toward population centers downwind.

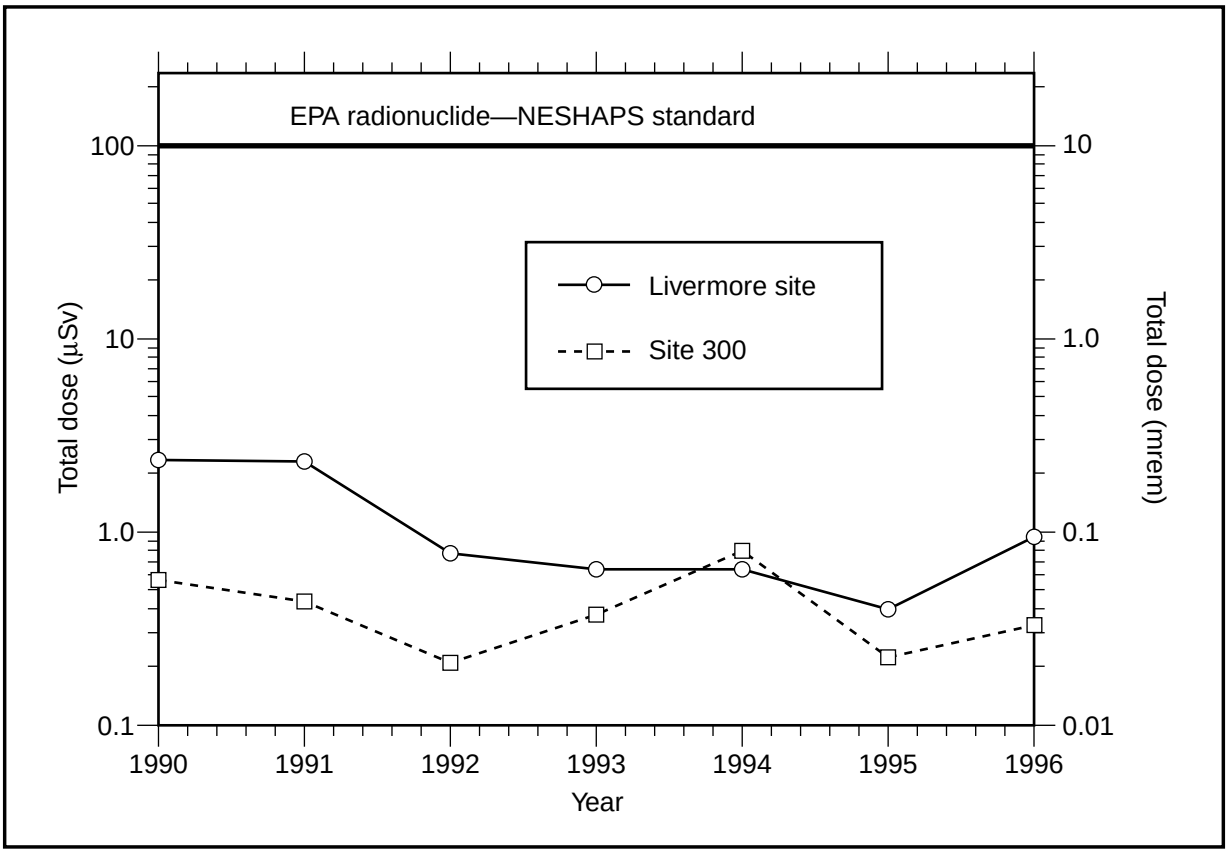

Figure 12-1. Dose to the sitewide maximally exposed individual member of the public, 1990 to 1996.

The corresponding collective EDE from Site 300 operations in 1996 was 10.0 person-rem (0.100 person-Sv), due almost entirely to explosives experiments (classified as point-source emissions). The total collective EDE value is very similar to the 1995 value of 7.7 person-rem (0.77 person-Sv). These differences are the result of differences in the amounts of high explosives and depleted uranium used each year in explosives experiments.

As shown in **Table 12-5**, these population doses caused by LLNL operations are several thousand times smaller than ones from natural background radiation.

Table 12-4. Doses (in μSv) calculated for the site-wide maximally exposed individual for the Livermore site and Site 300, 1990 to 1996.

Year	Total dose	Point source dose	Diffuse source dose
Livermore site			
1996	0.93	0.48	0.45
1995	0.41	0.19	0.22
1994	0.65	0.42	0.23
1993	0.66	0.40	0.26
1992	0.79	0.69	0.10
1991	2.3	—[a]	—[a]
1990	2.4	—[a]	—[a]
Site 300			
1996	0.33	0.33	0.0045
1995	0.23	0.20	0.03
1994	0.81	0.49	0.32
1993	0.37	0.11	0.26
1992	0.21	0.21	—[b]
1991	0.44	0.44	—[b]
1990	0.57	0.57	—[b]

[a] Diffuse source doses were not reported separately from the total dose for the Livermore site for 1990 and 1991.

[b] No diffuse emissions were reported at Site 300 for years prior to 1993.

The larger value for Site 300 compared to the Livermore site is traceable primarily to the highly conservative assumptions we make about the Site 300 explosives experiments, especially regarding the fraction of radioactive material that is aerosolized and the height and trajectory of the explosive-debris cloud. This conservative modeling methodology over-predicts the quantity of radionuclides released to air by at least a factor of five, we believe, and over-estimates the long-range dispersal of material in these experiments (see Supplement 12-3).

Table 12-5. Comparison of background and LLNL radiation doses, 1996.

Location/ Source	Individual dose[a]		Population dose[b]	
	(μSv)	(mrem)	(person-Sv)	(person-rem)
Livermore site sources				
Atmospheric emissions	0.93	0.093	0.011	1.1
Site 300 sources				
Atmospheric emissions	0.33	0.033	0.10	10
Other sources[c]				
Natural radioactivity[d, e]				
Cosmic radiation	300	30	1,900	190,000
Terrestrial radiation	300	30	1,900	190,000
Internal (food consumption)	400	40	2,500	250,000
Radon	2000	200	12,500	1,250,000
Medical radiation (diagnostic procedures)[e]	530	53	3,300	330,000
Weapons test fallout[e]	11	1.1	68	6,800
Nuclear fuel cycle	4	0.4	25	2,500

a For LLNL sources, this dose represents that experienced by the sitewide maximally exposed individual member of the public.

b The population dose is the collective (combined) dose for all individuals residing within an 80-km radius of LLNL (approximately 6.3 million people for the Livermore site and 5.2 million for Site 300), calculated with respect to distance and direction from each site.

c From National Council on Radiation Protection (NCRP 1987a and 1987b).

d These values vary with location.

e This dose is an average over the U.S. population.

Summary and Conclusion

The annual radiological dose from all emissions at the Livermore site and Site 300 in 1996 was found to be well below the applicable standards for radiation protection of the public, in particular the NESHAPs standard for DOE facilities, which limits total annual emissions of radionuclides to the ambient air to 100 μSv/y (10 mrem/y). Using EPA-mandated computer models, actual LLNL meteorology, and population distributions appropriate to the two sites, the dose to the LLNL sitewide maximally exposed members of the public from 1996 operations were:

- Livermore site: 0.93 μSv (0.093 mrem) (45% from point-source emissions, 55% from diffuse-source emissions);

- Site 300: 0.33 μSv (0.033 mrem) (99% from explosive experiments, classified as point-sources, 1% from diffuse-source emissions).

The major radionuclides accounting for the doses were tritium at the Livermore site and the three isotopes in depleted uranium (^{238}U, ^{235}U, and ^{234}U) at Site 300.

The collective effective dose equivalent or population dose attributable to LLNL operations in 1996 was estimated to be 0.011 person-Sv (1.1 person-rem) for the Livermore site and 0.10 person-Sv (10 person-rem) for Site 300. These doses include exposed populations of 6.3 million people for the Livermore site and 5.2 million for Site 300, living within a distance of 80 km from the site centers, based on 1990 census data.

Table 12-5 compares the individual and collective radiation doses from atmospheric releases at LLNL to other sources of radioactivity to which the U.S. population is exposed. The dose to the maximally exposed member of the public resulting from Livermore site and Site 300 operations is seen to be about 3000 times smaller than the doses from background radiation (see also **Figure 12-2** in Supplement 12-1 below), and the population dose from LLNL operations is about 200,000 times smaller than those caused by natural radioactivity in the environment.

We conclude that the potential radiological doses from LLNL operations were well within regulatory standards and very small compared to doses normally received by these populations from natural background radiation sources, even though highly conservative assumptions were used in the determinations of LLNL doses. Thus, the maximum credible doses show that LLNL's use of radionuclides had no significant impact on public health during 1996.

Chapter 12 Supplements

Supplement 12-1: Radiation Basics

Natural and Man-Made Radiation: By far the greatest part of radiation received by the world's population comes from natural sources—primarily cosmic rays that impinge on the earth's atmosphere from space and radionuclides naturally present in our environment, such as radioactive materials in soil and rocks. Among these terrestrial sources are carbon-14, potassium-40, rubidium-87, uranium-238, thorium-232, and radioactive elements, such as radon, that arise from decay of uranium and thorium. The source of human exposure to natural radiation can be external (from substances staying outside the body) or internal (from substances inhaled in air or ingested in food and water). Individual doses vary with location. The level of cosmic radiation increases with altitude, because there is less air overhead to act as a shield, and the earth's poles receive more cosmic radiation than the equatorial regions, because the earth's magnetic field diverts the radiation. The levels of terrestrial radiation differ from place to place around the United States and around the world, mainly owing to variations in soil and rock composition.

Adding to this pervasive natural or background radiation is man-made radiation from radionuclides used in medicine, consumer products, the production of energy, and the production of nuclear weapons. Exposure to man-made sources can be controlled more readily than exposure to most natural sources. However, nuclear explosives tested in the atmosphere in the 1950s and 1960s spread radioactivity across the surface of the globe, and the nuclear reactor accident at Chernobyl in 1986 affected a large area. At present, medical treatment is the largest common source of public exposure to man-made radiation. Individual medical doses vary enormously—someone who has never had an x-ray examination may receive zero medical dose while patients undergoing treatment for cancer may receive many thousands of times the annual average dose they would receive from natural radiation. Another source of public exposure to man-made radiation is consumer products, including luminous-dial watches, smoke detectors, airport x-ray baggage inspection systems, and tobacco products.

Radioactivity: Generally, naturally occurring isotopes are stable, but notable exceptions include carbon-14, potassium-40, thorium-232, uranium-235, and uranium-238, which occur naturally but are radioactive. Nuclear decay divides into three main categories: alpha, beta, and gamma. Alpha decay is the spontaneous emission of an alpha particle (a bound state of two protons and two neutrons—the nucleus of a helium atom) from a nucleus containing a large number of protons (most commonly 82 or more). Beta decay is the spontaneous conversion of a neutron to a proton in the nucleus with the emission

of an electron, and gamma decay is the spontaneous emission of high-energy photons (high-frequency electromagnetic radiation) by nuclei.

Radioisotopes decay at quite different rates; the "half-life," or length of time for half of the atoms to decay, spans a wide range from small fractions of a second to millions of years. For example, tritium (the radioactive form of hydrogen) has a 12.3-year half-life, compared to 24,131 years for plutonium-239.

Some radioisotopes decay by forming radioisotopes that in turn decay into other radioisotopes until a stable state is achieved. For example, an atom of uranium-238 can undergo alpha decay, leaving behind a daughter, thorium-234, which is also radioactive. The transformations of the decay chain continue, ending with the formation of lead-206, which is a stable isotope.

Radioactivity can be hazardous because radiation (alpha particles, beta particles, or gamma rays) can be released with great energy. This energy is capable of altering the electronic configuration of atoms and molecules, especially by stripping one or more electrons off the atoms of the irradiated material, thereby disrupting the chemical activity in living cells. If the disruption is severe enough to overwhelm the normal restorative powers of the cell, the cell may die or become permanently damaged. Cells are exposed to many naturally occurring sources of disruption, including naturally toxic chemicals in food, microbes that cause disease, high-energy radiation from outer space (cosmic rays), and heat and light (including the sun's rays, which can cause sunburn and skin cancer). Consequently, cells and living organisms have evolved the capacity to survive limited amounts of damage, including that caused by radioactivity.

Three main factors determine the radiation-induced damage that might be caused to living tissue: the number of radioactive nuclei that are present, the rate at which they give off energy, and the effectiveness of energy transfer to the host medium, i.e., how the radiation interacts with the tissue. Alpha radiation can be halted by a piece of paper and can scarcely penetrate the dead outer layers of skin. Radioisotopes that give off alpha radiation are generally not health hazards unless they get inside the body through an open wound or are ingested or inhaled. In those cases, alpha radiation can be especially damaging because its disruptive energy can be deposited within a small distance, resulting in significant energy deposition in a few cells. Beta radiation from nuclear decay typically penetrates a centimeter or two of living tissue. It therefore deposits energy over many cells, decreasing the damage to any single cell. Gamma radiation is extremely penetrating and can pass through most materials, only being significantly attenuated by thick slabs of dense materials, such as lead.

Measurement of Radioactivity and Dose: The rate at which a nucleus decays is expressed in units of becquerels, abbreviated Bq, where 1 becquerel is one decay per second, or alternatively in curies, Ci, where 1 curie equals 3.7×10^{10} (37 billion) decays per second, or 3.7×10^{10} Bq (approximately equal to the decay rate of 1 gram of pure radium). Becquerels and curies are not measures of the effect of radiation on living tissue. This depends on the efficiency of energy deposition as the radiation traverses matter.

The amount of energy deposited in living tissue is called the "dose." The amount of radiation energy absorbed per gram of tissue is called the "absorbed dose," and is expressed in units of rads or grays (Gy), where 1 Gy equals 100 rads. Because an absorbed dose produced by alpha radiation is more damaging to living tissue than the same dose produced by beta or gamma radiation, the absorbed dose is multiplied by a quality factor to give the dose equivalent. The quality factor for alpha radiation is 20; for beta and gamma, 1. The dose equivalent is measured in units of rem or sieverts (Sv); 1 Sv equals 100 rem. Also commonly used are the millirem (mrem) and the millisievert (mSv), which are one-thousandth of a rem and sievert, respectively.

Just as one type of radiation can be more damaging than others, some parts of the body are potentially more vulnerable to radiation damage than others, so the different parts of the body are given weightings. For example, a given radiation dose from iodine-131 is more likely to cause cancer in the thyroid than in the lung. The reproductive organs are of particular concern because of the potential risk of genetic damage. Once particular organs are weighted appropriately, the dose equivalent becomes the "effective dose equivalent," also expressed in rem or sievert.

The effective dose equivalent (EDE) describes doses to individuals. When individual effective dose equivalents received by a group of people are summed, the result is called the "collective effective dose equivalent," often referred to as the "population dose," and is expressed in person-sievert or person-rem. Finally, to account for the long-term effects of radionuclides as they continue to decay and affect generations of people, we calculate the dose over many years, summing the effect over time. This is termed the "collective effective dose equivalent commitment." Most of our discussion in this chapter deals with the effective dose equivalent and the collective effective dose equivalent.

Doses from Natural and Man-Made Radioactivity: The average radiation dose from natural sources in the United States, according to the National Council on Radiation Protection and Measurement (NCRP 1987b), is 3.0 mSv/y (300 mrem/y). Approximately 0.3 mSv/y (30 mrem/y) of this exposure comes from high energy radiation from outer space (cosmic rays). Terrestrial sources, mainly radionuclides in

rock and soil, also account for approximately 0.3 mSv / y (30 mrem / y) of the average natural dose. Another significant part of the dose comes from radionuclides we ingest through food and drink, resulting in approximately 0.4 m Sv / y (40 mrem / y). Potassium-40 and carbon-14 are common radionuclides in food.

The remaining 2.0 mSv / y (200 mrem / y) or 67% of the average dose from natural sources in the United States comes from radon gas. Radon is one of the major radionuclides produced by uranium decay, and our inhalation dose is dominated by radon's short-lived decay products. **Figure 12-2** shows the distribution of annual radiation doses from natural and other common sources.

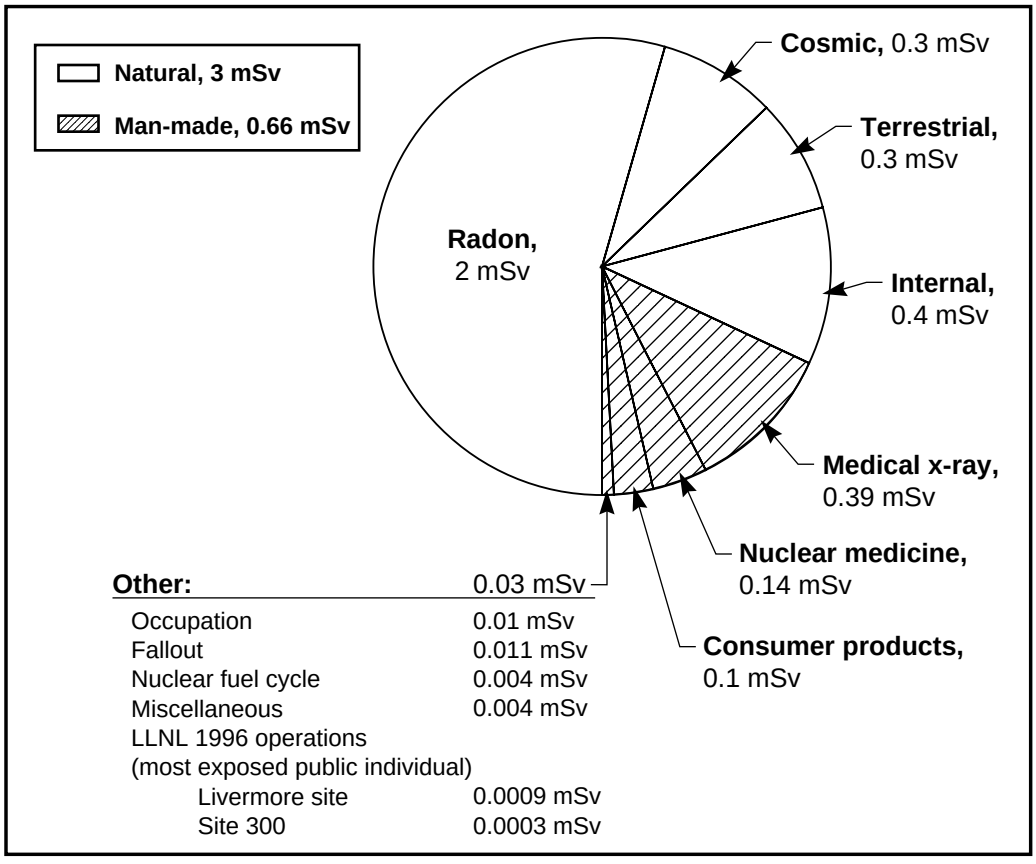

Figure 12-2. Typical annual radiation doses from natural and man-made sources (NCRP 1987b).

Radon dose varies significantly with geographic location. Levels several times higher than the average occur in some regions of the United States, while at LLNL and its environs doses as low as half the average are typical. Radon gas seeps out of the earth worldwide. Radon in water and natural gas provide additional but less important

sources of radon in homes. The United States Environmental Protection Agency (EPA) has instituted a major program to educate the public regarding the effects of naturally occurring radon (U.S. Environmental Protection Agency and U.S. Department of Health and Human Services 1986).

The dose received by any particular individual from natural background sources depends on other lifestyle choices or conditions besides place of residency, eating habits, and occupation. For example, the dose from cosmic radiation received in a one-way airplane flight between New York and Los Angeles is about 2.5 mrem; two U.S. coast-to-coast round trip flights give about the same radiation exposure as a standard chest x-ray.

We noted earlier that medical treatment is the largest common source of public exposure to man-made radiation, and most of it is delivered as medical x-rays. These contribute 0.39 mSv (39 mrem) to the average whole-body annual dose in the United States, but individual doses vary enormously. For example, a typical dental x-ray series results in a skin dose (not whole body) of approximately 2.5 mSv (250 mrem). Nuclear medicine contributes 0.14 mSv (14 mrem) to the average dose, and consumer products add 0.1 mSv (10 mrem). For a typical member of the public, radiation from medical procedures and consumer products result in a dose of approximately 0.63 mSv/y (63 mrem/y). The average dose from other man-made sources, including fallout from nuclear testing, is less than 0.03 mSv (3 mrem). As described in this chapter, the contributions from LLNL operations to the dose of even the most affected resident are on the order of 0.1 mrem/y or less, and would not be discernible on the scale shown in **Figure 12-2**; LLNL's contributions are listed under "Other" in the figure.

Supplement 12-2: Radiation Control Measures at LLNL

Radioisotopes used at LLNL include uranium, transuranics, biomedical tracers, tritium, and mixed fission products. Protection of employees and the public from the uncontrolled release of radioactive materials into the environment is a primary consideration for LLNL. This effort takes several forms, as summarized here.

When an operation or facility is designed, a thorough assessment of potential radiation hazards is conducted, and radioisotope-handling procedures and work enclosures are determined for each project, depending on the isotope, the quantity being used, and the type of operations being performed. Radioisotope handling and working environments include glove boxes, exhaust hoods, and laboratory bench tops. The controls might include limiting physical access and using shielding, filters, and remote handling equipment. Exhaust paths to the atmosphere include HEPA

(high-efficiency particulate air)-filtered stacks, stacks lacking abatement devices, roof vents, and ordinary room air ventilation channels. Facility Safety Analysis Reports and Facility Safety Procedures are written to document the need for specific measures and to spell out the requirements for maintenance, training, emergency response, and other administrative control measures.

When a facility is occupied for use, an Operational Safety Procedure (OSP) is written that specifies actions to be taken in conducting a research or development project. This procedure is reviewed by environmental analysts, industrial hygienists, and health physicists to assess the safety of the operation, its compliance with current occupational health and environmental standards, and the adequacy of proposed engineering and administrative controls. The OSP also specifies training requirements for personnel. This part of the control program enables LLNL personnel who work with radiation and radioactivity to recognize and prevent the execution of unsafe operations.

Another form of LLNL's radiation control program involves direct monitoring of the workplace environment. This includes sampling of the air and surfaces in facilities where radioactive materials are handled, and includes personal dosimetry and bioassay programs used to monitor potential worker exposure to direct radiation and radioactive isotopes. This monitoring program helps to determine the effectiveness of a facility's radiation control program as well as providing information on worker exposures.

The surveillance and effluent monitoring of radiation in air, water, soils, vegetation, and sewage, as discussed in Chapters 2 and 4 through 11 of this report, play an important role in LLNL's program to control radiation releases. These measurements can signal anomalous releases, should they occur, and directly gauge the degree of success of LLNL's radionuclide discharge control program in limiting exposures of the public.

Development of the Livermore Valley and the San Joaquin Valley has enlarged the populations and decreased the distance between sources of emissions and the residents who might be exposed. People live and work within several hundred meters of LLNL's boundaries. It is therefore increasingly important that our assessments provide the best information possible regarding the radiological impact of LLNL operations.

Supplement 12-3: Modeling Explosives Experiments at Site 300

Modeling releases to the atmosphere from explosive tests at Site 300 requires special attention compared to conventional stack or area sources. During experiments, an explosive device containing depleted uranium is placed on an open-air firing table and detonated. A cloud of explosive decomposition products promptly forms over the firing table, and disperses as it is carried downwind. (The uranium does not contribute to the explosive energy, which is entirely of chemical origin.) In the absence of measurements of the properties of the cloud, we assume for modeling purposes that it reaches an initial height and size governed by known empirical scaling laws for detonations, in which the scaling parameter is the TNT-equivalent explosive mass. Isotopic ratios for depleted uranium are used. The masses of the three uranium isotopes with atomic weights 238, 235, and 234 (occurring in depleted uranium in the weight-percentages 99.8, 0.2, and 5×10^{-4}, respectively) are multiplied by their respective specific activities to get the total number of curies for each isotope in the cloud.

LLNL's modeling of these Site 300 explosive tests to determine the resultant off-site doses is based on the CAP88-PC code. CAP88-PC simulates each explosive experiment or shot as a low-level, steady-state (year-long), stack-type emission occurring over flat terrain with meteorological data appropriate to annual average conditions at Site 300. An alternative modeling methodology that treats these transient explosive events as short-duration puffs, and that incorporates some of the effects of the hilly terrain at Site 300, was submitted for approval in 1992 (*LLNL NESHAPs Project Quarterly Progress Repor*t, Biermann et al. 1993), but LLNL was directed by EPA to use the CAP88-PC code for these calculations despite the recognized difficulties.

Several conservative assumptions are made in the absence of detailed data on the explosive experiments. We assume that: (1) 100% of the depleted uranium present in the experiment is completely aerosolized and dispersed as a cloud; (2) the median particle size is the CAP88-PC default value of 1 micrometer; (3) the lung clearance class for inhaled material is class Y. (Note: Clearance of inhaled material from the lung to the blood or to the gastrointestinal tract depends on the chemical form, e.g., U_3O_8, of the radionuclide, and is classified as D, W, and Y, respectively, for clearance times of order days, weeks, and years.) These assumptions may produce a dose that is too high by a factor of 10 or more. We believe a more realistic release-to-air fraction for the uranium is no greater than 0.2, but we lack sufficient documentation to use a value other than 1.0. Also, the median particle size may be much larger than 1 μm and a sizable fraction of the aerosolized particles might be more properly characterized by lung clearance class D, which produces a dose by inhalation of depleted uranium that is smaller by a factor of about 16 compared to class Y.